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Diameter Quality Control of Nb_3Sn Wires for MQXF Cables in the U.S.

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***Abstract*— The 0.850 ± 0.003 mm Nb_3Sn wires for the low-beta quadrupole magnets "MQXFA" procured for the U.S. LHC Accelerator R&D Program (LARP) and the U.S. High Luminosity LHC Accelerator Upgrade Project (US HL-LHC AUP, or simply AUP) are received at Lawrence Berkeley National Laboratory (LBNL). There, the wires are respooled and then fabricated into Rutherford cables for winding coils. As part of the quality control (QC) program, AUP obtains from the wire manufacturer values of the maximum, average, minimum, and standard deviation of the two orthogonal axes, which are assessed prior to shipment approval. At LBNL, a dual-axis optical micrometer is used to measure the wire diameter of each spool every ~30 cm prior to cabling. This helps decide whether wire pieces with abnormal diameters should be distributed across the cable cross section, in order to improve cable parameter quality and mechanical stability consistency.**

This paper presents (1) diameter data of LARP cables and of the first AUP cables made using wires acquired under LARP, (2) our deviation acceptance/rejection justification, and (3) the impact of wire diameter statistics on cable fabrication.

***Index Terms*—Superconducting magnets, niobium-tin, Rutherford cable, quality management, Large Hadron Collider**

I. Introduction

THE US HL-LHC AUP is a Department of Energy (DOE) Office of Science High Energy Physics project, with a budget in excess of 200 million USD. It is established to fulfil a U.S. contribution to CERN's High Luminosity Upgrade of the LHC [1] and is the projectized successor of LARP [2]. Within its scope is the fabrication of ten Q1/Q3 low-beta "inner triplet" quadrupole magnets MQXFA. (Note: Q2 MQXFB are made by CERN. The short model and prototype quadrupole magnets are known as MQXFS and MQXFP, respectively.)

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LBNL is the manufacturer of all the Nb_3Sn Rutherford cables for LARP and AUP [3]. The target lengths of MQXFA and MQXFP cables are approximately 470 m, including samples for mechanical and electrical QC as well as archive. The target length of MQXFS cables is approximately 180 m. After accounting for twist pitch, startup, end losses etc., the total wire length needed for a 40-strand MQXFA or MQXFP cable is approximately 20 km, and for an MQXFS cable approximately 8 km. The LBNL cabling machine has only one rotating base ("bay") on which up to 60 wire spools can be mounted but on one side of the bay only. Advantages of this design include identical path length of all the spools (save for the slight difference due to the fact that the spools are mounted in two concentric circles) and easy access to planetary chains. One drawback, however, is that the maximum wire mass is more restricted, due to the high angular momentum of the large diameter bay. The maximum wire length that can be mounted is dependent on the wire diameter (since it is mass limited), and the maximum cable length that can be fabricated further depends on the cable lay pitch (a short cable lay pitch means the wires' lateral-traverse-to-cable-length ratio is high). For MQXF cables using 0.850 mm diameter Nb_3Sn wires, the maximum cable length is approximately 1 km, which is roughly 10% of the theoretical yield length of typical production billets of accelerator-grade internal tin Nb_3Sn nowadays [4].

Because of this difference between the typical wire length as manufactured and the required wire length for an MQXF cable—as well as other technical reasons—the strand delivered by the wire manufacturer has to be "respooled" onto the spools specifically designed for the cabling machine. For the mass of typical Nb_3Sn billets, wire manufacturers usually use plastic

TABLE I
Cable Codes according to the Materials Naming Scheme

Cable Code	Description
P23	1st gen. MQXFA cables, using un-annealed 108/127 wires
P33	1st gen. MQXFA cables, using annealed 108/127 wires
P35	1st gen. MQXFA cables, using annealed 132/169 wires
P43	2nd gen. MQXFA cables, using un-annealed 108/127 wires
P45	2nd gen. MQXFA cables, using un-annealed 132/169 wires
P47	2nd gen. MQXFA cables, using un-annealed 144/169 wires

P20s and P30s series are first generation MQXFA cables.
P40s series is second generation MQXFA cables.
P20s and P40s series use un-annealed strands.
P30s series uses annealed strands.

spools with hub diameter of 6.5” (~16.5 cm) to 7.5” (~19 cm) and flange diameter of 12” (~30.5 cm) to 15” (~38.1 cm). For mechanical strength and reduction of dead mass on the rotating bay, LBNL uses aluminium spools (“Al spools”) with hub and flange diameters of 4” (~10.2 cm) and 6.5” (~16.5 cm), respectively, on the cabling machine. When pre-cabling annealing is applied (see Section II below), LBNL would first respool the wires from the plastic spools onto stainless steel spools (“SS spools”, 3” (~7.6 cm) hub diameter and 8” (~20.3 cm) flange diameter), and then after annealing, from the SS spools onto the Al spools. During respooling, LBNL uses a dual-axis optical micrometer (a Keyence LS-7000 series) to verify the wire diameter in-line. Between respooling, certified gauge pins are measured to monitor calibration drift. Data are acquired every foot (~30 cm).

In this paper, we will present the wire diameter quality control (QC) at the supplier and during respooling for MQXF cables at LBNL, reporting some events observed, their resolution, and the rationale behind. Some of these cables were fabricated under LARP, while some were under AUP. In either case, however, all the wires (~800 km) were procured under the scope of LARP either directly or via the U.S. Conductor Development Program (CDP) [5], by Brookhaven National Laboratory (BNL), by Fermi National Accelerator Laboratory (FNAL), or by Lawrence Berkeley National Laboratory (LBNL). Among them, two large orders—FNAL PO’s #624035 and #632982, procured according to the “HiLumi Specification” [6]—cover in excess of 600 km of wire.

II. Wire and Cable

The Nb_3Sn wires used in the cables presented are all RRP® wires made by OST (or B-OST after the acquisition of OST by Bruker in November 2016 [7]). However, the number of subelements in the restack varies in these wires. Three restack designs were used: 108/127, 132/169, and 144/169. The 169 restack billets were only used in some MQXFP and MQXFS, but not in MQXFA cables. The Cu:non-Cu ratio and wire diameter of these three restack designs are nominally identical, 1.2 and 0.850 mm, respectively. Their subelement diameters are estimated to be 55 µm (108/127), 50 µm (132/169), and 48 µm (144/169), according to the formula by Cooley *et al.* [8].

There are two major “generations” of cable design. The difference between the so-called “first generation” and “second generation” cables is with the keystone angle, reduced from 0.55° to 0.40°, following the 2014 HL-LHC/LARP International Review of the Superconducting Cables for the HL-LHC Inner Triplet Quadrupoles. Furthermore, for most first generation cables, the fabrication procedure includes annealing the strands before cabling at 170°C for about 16 hours, while all second generation cables were fabricated using un-annealed strands. This pre-cabling annealing was applied initially with the intention to reduce the number of sheared subelements in the strands during cabling by softening the Cu matrix, as well as to reduce the amount of cable residual twist. However, it was subsequently deemed that the pre-cabling annealing has insufficient evidence of a positive impact on reducing the number of sheared subelements to justify the added schedule and cost and the substantial risk for such a process, and the annealing step was removed.

The Materials Naming Scheme adopted by LARP and AUP [9] has a convenient way to identify these different cable designs using different wire architectures and different fabrication procedures. All LARP and AUP cables start with the letter “P” (as are the wires). The P20s and P30s series are first generation cables, whereas the P40s (and P50s, not used) series is second generation cables. The P20s and P40s series are without pre-cabling annealing, while the P30s series (and P50s, not used) is with pre-cabling annealing. The Px3 (e.g. P23, P33, P43) cables use 108/127 strands, Px5 (e.g. P35. P45) cables use 132/169 strands, and Px7 (e.g. P47) cables use 144/169 strands. Table I summarizes the codes of the cables presented in this paper. For completion, odd number cables have a 316L stainless steel core, even number cables are without (none presented in this paper).

III. Diameter Data

A. Supplier QC

As part of the quality assurance management plan [10], the two aforementioned large orders by FNAL require the vendor to submit QC packages to the procuring laboratory when requesting an approval to ship. The required QC package includes a range of diameter data for every spool delivered, such as averaged diameter in orthogonal directions (diameter x and diameter y), standard deviation of each of diameter x and diameter y, averaged ovality, and maximum ovality, where ovality is defined as the absolute difference between diameters x and y.

B-OST diameter QC was performed on commercially available laser, optical, or LED micrometers, acquired roughly every metre. One of their systems acquires the diameter values on fixed axes. But since the wire (which has a twist) can and does rotate during a run, the diameter orientation measured is not stationary with respect to any reference system. Another system that was also used returns one value for diameter and one value for ovality, which are then manipulated to create the two diameter values, where the larger value is captured as diameter x and the smaller of the two as diameter y. The data from this latter system in an x-y diameter plot therefore would appear skewed, but are nonetheless comparable to those acquired using the fixed-axis system.

Fig. 1a shows the spool-averaged diameter y plotted against diameter x, using supplier QC data. The main issue is that some diameter x data points are outside the specification limits of 0.850 mm ± 0.003 mm. They came from four billets purchased under FNAL PO #624035: two from Shipment A, and two from Shipment B, to be discussed further below. These billets were eventually accepted with deviation reports. All diameter y data points (as well as the data of averaged diameter, i.e. $(x+y)/2$, not shown) are within specification.

Fig. 1b shows the spool-averaged ovality plotted against spool-averaged x-,y-averaged diameter, using supplier QC data. The individual datum maximum ovality (shown as error bar) is not used as a QC parameter for acceptance, because outliers can be introduced by vibration or dust particles. By data acquisition definition, the ovality is always non-negative. Some spools with high ovality are suspected to have been caused by over tightening the guide rollers during inspection at B-OST.

B. *Verification QC*

LBNL collects a large amount of diameter data (~3,000 dual-axis points per km of wire) during respooling, which LARP/AUP uses for verifying the supplier QC. At the beginning of FNAL's PO #624035, LBNL verification data showed that, in addition to the four billets with supplier QC data showing diameter x being out of specification, there are further billets with diameters well above specification. Moreover, the LBNL verification data cloud showed an offset toward diameter growth compared to supplier QC data (Fig. 2).

An investigation was launched and a site visit was made by project representatives. The investigation included round robin diameter checks using reference sample spools between B-OST and LBNL, and between LBNL and BNL, and it concluded that the B-OST laser micrometer calibration was underestimating the diameter. A second cause was also identified as a die out of calibration, which was consequently retired.

C. *Pre-cabling annealing impact on diameter QC*

For some of those first generation cables receiving a pre-cabling annealing, diameter data were collected both during the respooling from the wire manufacturer's plastic spool to the LBNL SS spool ("pre-annealing data") and during the respooling from the SS spool to the Al spool ("post-annealing data"). A histogram distribution plot shows that the pre-cabling annealing causes a diameter expansion of ~0.8 μm (Fig. 3).

IV. Discussion

A. *Deviation Acceptance*

In Rutherford cables, heavy plastic deformation is imparted on the wires at the cable edges, and where a keystone angle is present, the minor edge suffers the most deformation. Cabling experience at LBNL suggests that when a cable is made narrower (i.e. decreased width), *ceteris paribus*, the wires on the top and bottom broad faces of the cable may not distribute accordingly, and the three wires at the cable edge (the "triplet") would absorb most of the increased deformation. Similarly, using the same MQXF cable parameters, when the wire diameter is increased, the concern on cable quality is the increased deformation at the cable edge.

The P33 and P35 cables with pre-cabling annealing have the same cable cross section design as the P23 cables without pre-cabling annealing. As shown in Fig. 3, after pre-cabling annealing, the median wire diameter of the P33 and P35 wires is above 0.853 mm, the upper specification limit. No fabrication issues were observed during the P33 and P35 production runs, and post-production QC on samples including metallography and RRR showed that these cables have equally acceptable performance as the P23 cables. Based on this experience, LBNL feels confident that for P43, P45, and P47 cables, which has a lower keystone angle (i.e. less deformation on the minor edge), wire

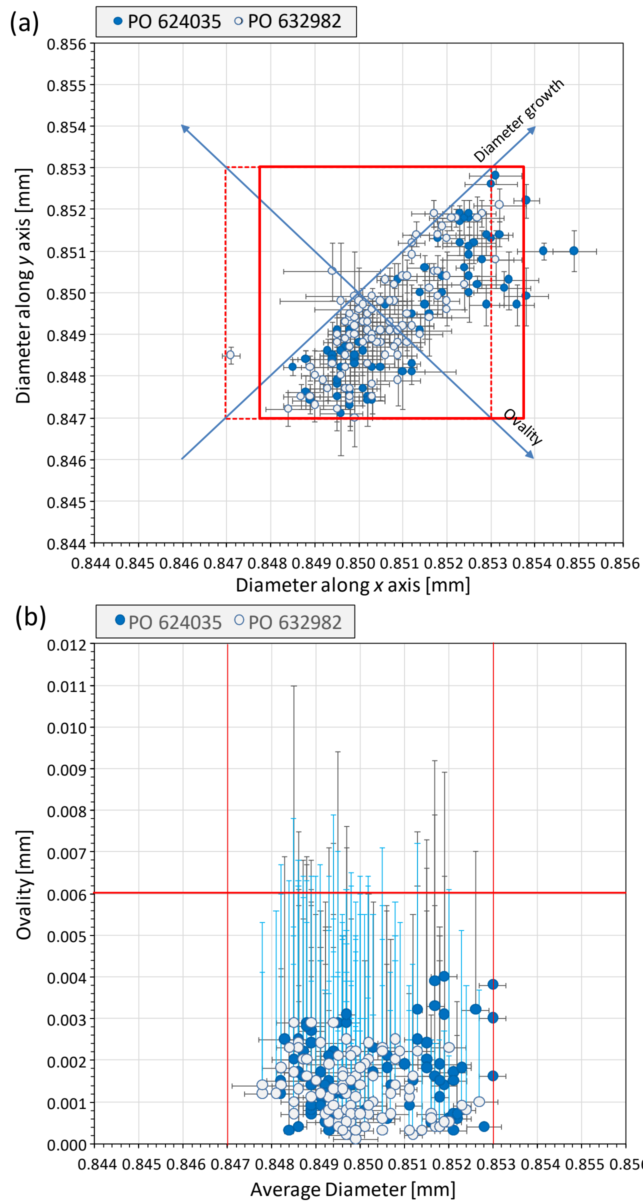

Fig. 1. Supplier's dual-axis diameter data (averaged per spool) from two FNAL orders totaling ~600 km. Each datum is the average over the measurements, and the number of measurements averaged is roughly proportional to the length of the spool---measurement rate is at least once per metre. In Fig. 1(a), diameter y is plotted against diameter x. The majority of data, which were acquired using the diameter-ovality system (explained in §III.A), skew towards the right because the larger value from the two axes' reading is captured as diameter x and the smaller of the two as diameter y. The diagonal arrows drawn on the graph indicate increasing diameter growth (single-headed arrow) and ovality (double-headed arrow). The dotted-line red box indicates the specification and target range for the data cloud. The solid-line red box shows that the actual data shifted to a slightly higher diameter. The skew is 0.74 μm and equal to half of the average ovality for all diameters in Fig. 1 (b), which is 1.48 μm. The over-diameter data points in the x-direction are from four billets from FNAL PO #624035. But these billets' x-,y-averaged diameters were at or under specification limit. The error bars indicate one standard deviation in the respective axes. In Fig. 1(b), ovality is plotted against diameter. The error bars are the maximum ovality of the wire spool and the standard deviation of the averaged diameter. The red lines indicate the boundaries according to specification.

diameter deviation up to 1 μm above upper specification limit can be tolerated.

If, however, the wires going into a cable have a bimodal diameter distribution, efforts will be made to blend or mix the

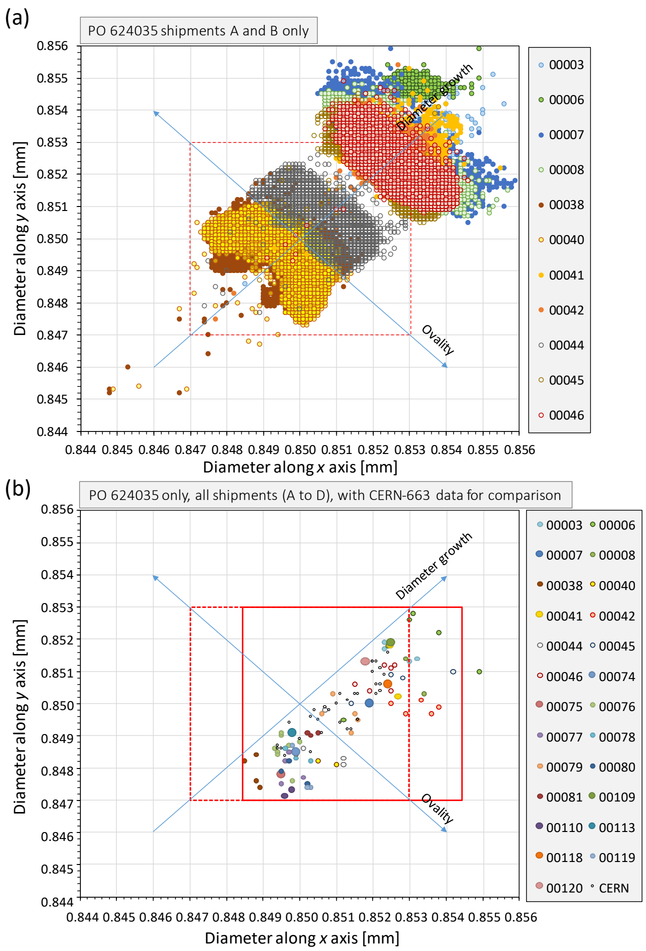

Fig. 2. (a) LBNL's dual-axis diameter data (~90 km or over a quarter million data points) from FNAL PO #624035, Shipments A & B only. The number of measurements is proportional to the used length of the billet—measurement rate is every ~30 cm. (b) Supplier's dual-axis diameter data (averaged per spool) from FNAL PO #624035, all shipments. The size of the markers is inversely proportional to the number of spools per billet. The dotted-line red box indicates the specification and target range for the data cloud. The solid-line red box shows that the actual data shifted to a slightly higher diameter. The skew here is a weighted average of the ovality taken from the quarter million data points in Fig. 2(a). The over-diameter data points are from four billets from Shipments A & B of FNAL PO #624035.

wires to avoid having all the large (or small) diameter wires grouped and placed adjacent to each other, which may have an impact on the keystone angle.

B. Impact on Length Estimates

Some spools from FNAL PO #632982 were flagged during approval to ship because the supplier QC diameter average with standard deviation was at or above the control limit. Respooling diameter data of these spools from LBNL verification QC showed good agreement with supplier reported data: average diameter is within specification limit, but the standard deviation is larger than the difference between the upper specification limit and the average diameter. Furthermore, LBNL found that 10% or more individual data points lie up to 1 μm above the upper specification limit. Such deviation was tolerable for cabling, as described above.

However, one of these spools, PO08S00191A03U, reported to be 3016 m long, revealed a different issue. LBNL always performs an inspection upon receiving delivered spools and prior to acceptance, by measuring the gross weight, estimating the net weight by deducting the tare weight based on spool style, and then computing the wire length based on linear density. Using the nominal diameter (0.850 mm) and density (8.75 g cm^{-3}), LBNL estimated PO08S00191A03U's length to be 3025 m. Using the smaller of the two lengths (that reported by supplier and that estimated by LBNL), six pieces of 502 m were mapped for an AUP MQXFA cable. Unfortunately, at the end of the respool this wire came up shorter than 3016 m by 18 m and the last respool had to be replaced. The inspected diameter during respooling was 0.8524 ± 0.0007 mm. The linear density due to this off-nominal diameter is about 0.6%, exactly the length short on the spool. This shows that mapping length margin should be estimated with an additional buffer to account for weight conversion using nominal diameter, in case the wire diameter is at the upper end of the specification range.

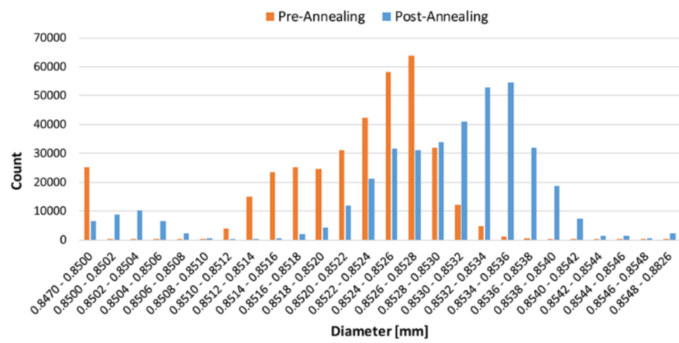

Fig. 3. Comparison of respooling wire diameter in P33 and P35 cables before and after pre-cabling annealing (from >750,000 dual-axis data). The average diameter increase is approximately 0.8 μm. Over 55% of the post-annealing data are above 0.853 mm, and over 3.5% of the post-annealing data are above 0.854 mm. Note that the first and last bins have different bin widths.

V. Conclusion

The systematic diameter verification at LBNL of delivered Nb_3Sn wire proves to be helpful in identifying off calibration issues at the wire manufacturer and in ensuring MQXF cable quality. Study of first generation cables shows that pre-cabling annealing causes a diameter expansion of approximately 0.8 μm, which does not have an observable impact on cable fabrication. Wire oversized by a similar amplitude is thus deemed tolerable, and justification to accept diameter deviation is based on this finding. However, grouping oversized wire adjacent to each other should be avoided during cable fabrication. Finally, wire length estimates using measured weight and nominal diameter may require added margin.

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